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A comprehensive end-of-life strategy decision making approach to handle uncertainty in the product design stage

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Keywords
End-of-life, uncertainty, fuzzy logic, expected value, product design, decision making

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This study employs fuzzy logic to evaluate uncertain component End-of-Life (EOL) options in the design stage. Determining EOL strategies during the product design stage can be complex. For example, EOL strategies for retired bicycle components are various and may change with geographic location. Thus, adopting fixed EOL strategies in the product design stage may not always be appropriate; the element of uncertainty should be considered. Limited research has examined uncertainty of EOL strategies during the design stage. Moreover, the evaluation of EOL strategies in a comprehensive manner has not been shown in a realistic case study. These facts motivate this investigation. Fourteen evaluation criteria are used to generate a comprehensive framework for assessing seven EOL strategies. The evaluation process generates the likelihood for each of these strategies by aggregating fuzzy set operations and a left-right fuzzy ranking method. By using SUMPRODUCT calculation for these weights/probabilities and input sustainability value (i.e., cost, environmental impact and labor time), expected values are derived to represent the sustainability values for each EOL strategy. A Technique-for-Order-of-Preference-by-Similarity-to-Ideal-Solution (TOPSIS) based method is employed to identify the appropriate EOL strategy for each component/product. A refrigerator is used as a case study to illustrate the methodology. This study addresses the uncertainty involved in identifying an EOL strategy for a specific product component during the design stage through the use of fuzzy logic. The method closes a gap in the current EOL strategy assessment criteria and introduces a comprehensive evaluation framework to capture multiple strategic perspectives by incorporating fourteen key evaluation criteria.

Key Words: End-of-Life, Uncertainty, Fuzzy Logic, Expected Value, Product Design, Decision Making

1. Introduction

Recently, dramatic changes have evolved in the competitive landscape for companies. A carefully constructed vision is needed to satisfy global market demands such as shorter lead time, just-in-time production, and product variety. Product design has been suggested as an effective vehicle to satisfy such demands (Ma and Kremer 2016a). Product design is a complicated and creative process that harmonizes the needs of customers, the strategy requirements of companies, and the environmental constraints of regulatory agencies. Four stages comprise product design: problem definition, conceptual design, preliminary design, and detail design; all design requirements must be met through these stages. Because approximately 70% of product cost (Appelqvist et al. 2004) and 80% of product quality (Dowlatshahi 1992) are determined during the design stage of product development, product design is a critical concern for developers.

One of the above mentioned dramatic changes is the focus on sustainability, especially in product life cycle management, due to ever-increasing awareness of environmental and social concerns. Product life cycle management addresses both a product's entire life and its end-of-life (EOL) strategies. Certain EOL strategies can generate significant energy waste, environment pollution, and cost across the entire product life cycle; accordingly, research has increasingly tended to focus on EOL strategies taking them into account during the design stage. The simultaneous consideration of product design and life cycle management in the design stage is expanding; many researchers have developed new product design methodologies to support this expanded view (e.g., Lee et al. 2001; Ma and Kremer, 2014a; Li et al. 2008; Abdullah et al. 2015; Ma and Kremer 2016b; Chung et al. 2016). The EOL decision making depends on many factors. These factors come from a wide spectrum of stakeholder interests and component aspects, and the resulting perspectives vary across industries and geographies (e.g., Kikke et al. 1998; Rose 2001; Bufardi et al. 2004; Li et al. 2008; Ziout et al. 2013; Ma and Kremer, 2014b; Ma and Kremer 2015). To the best of our knowledge, however, no research has yet considered evaluating EOL decision factors from a comprehensive perspective at the early design stages. Hence, this need for development of such an EOL decision making approach motivates this study.

Both the entire life cycle-based and the EOL-based methods hold a critical assumption: the EOL option is fixed. Thus, EOL strategies have typically been predetermined, which means that EOL strategies are treated as constant inputs to various methods (e.g., Bryant et al. 2004; Kreng and Lee 2004a; Kreng and Lee 2004b; Li et al. 2008; Lai and Gershenson 2009; Yan et al. 2012; Ji et al. 2012). Predetermining EOL strategies is not always appropriate, and EOL decision making is often governed by several uncertain aspects such as remaining life time and/or repair complexity. Scant research considers uncertainty in EOL strategies and product design simultaneously. Therefore, another purpose of this research is to develop and present an approach to handle uncertainty in EOL strategy analysis and to illustrate its implementation at the design stage of a product.

2. Literature Review

Since the dawn of the 21st century, an increase in product variety requirements along with a surge in demographic growth has generated a huge amount of retired products each year. Concerned with environmental pollution and ecological destruction, the European Union (EU) has formulated regulations based on the principle of extending a producer's environmental responsibility (Walls 2006), requiring manufacturers to be more responsible for the life cycle management of their products—especially at the EOL phase. In response to this mandate, many researchers have conducted investigations specifically addressing the EOL phase. Kiritsis et al. (2013) defined an EOL product as one retired from the functional environment for social or legal reasons. In the following section, several product EOL strategy definitions and selection methods are reviewed and summarized.

Many EOL strategy definition and categorization methods have evolved over decades. Marco et al. (1994) identified seven types of EOL strategies: reuse, remanufacturing, primary recycle, secondary recycle, incineration, landfill and special handling and provided the guidelines to classify the retired products. Ishii et al. (1995) summarized the work of Marco et al. (1994) and found that reuse and remanufacturing are highly correlated, incineration and landfill are overlapped with many similarities. They re-categorized into four types: remanufacturing/reuse, primary recycling, secondary recycling, and disposal in order to simplify the EOL strategy selection procedure. Stevels (1997) studied pertinent works and refined EOL strategies into four new types, labeling them reuse, remanufacturing/refurbishing, recycling, and incineration. A comprehensive selection framework was developed based on this categorization. Ijomah et al. (1999) believed all retired products can be linked to second life cycle and disposal/incineration/landfill have really bad influence to environment. With these considerations, they presented five types: reuse, repair, reconditioning, remanufacture and recycling. Rose (2001) expanded on that work, specifying six EOL strategies: reuse, service, remanufacturing, recycling with disassembly, recycling without disassembly and disposal after analyzing hundreds of products. Using a slightly different approach, Li et al. (2008) and Chung et al. (2012) defined three strategies based on use frequency: reuse, recycle, and disposal. Remery et al. (2012) categorized six EOL strategies: reuse, remanufacturing, recycling with disassembly, recycling without disassembly, incineration with energy recovery and disposal, and developed a qualitative analysis based EOL strategy determination approach with environmental sustainability consideration. A categorization issued by the Center of Remanufacturing and Reuse (CRR) (2013) includes nine EOL strategies: remanufacturing, reconditioning/refurbishing, reuse, repurposing, repair, recycling, composting, incineration, and landfill — based on the classification and summarization of former work in both industry and academia.

The EOL definition literature is summarized in Table 1. As it can be followed from this table, most of the extant definitions provide guidelines and/or descriptions that can be used in non-equation-based (qualitative) analysis, but fall short in representing or narrowing down EOL options through equation-based (quantitative) means. Equation-based analysis provides a quantitative way to capture and evaluate the features of EOL strategies. Through numerical representation of EOL strategies, the key performance such as cost, environmental influence and social impact can be gauged in a more accurate manner potentially benefiting many relevant decisions. Therefore, equation-based analysis may be perceived to outperform non-equation-based analysis in EOL strategy comparisons of both theoretical and practical implementation.

Table 1 EOL Definition Literature Summary

Author/Year	# of EOL Strategy	Application		Note
		Equation-Based Analysis (Quantitative)	Non-Equation-Based Analysis (Qualitative)	
Marco et al., 1994	7	--	X	
Ishii et al. 1995	4	--	X	
Stevels, 1997	4	--	X	
Ijomah et al., 1999	5	--	X	
Ross, 2001	6	--	X	
Lee et al., 2001	7	X	X	Develop residual cost formula for Marco et al. (1994)'s work
Li et al., 2008	3	--	X	
Chung et al., 2012	3	--	X	Adopt Li et al. (2008)
Remery et al., 2012	6	--	X	

CRR, 2013	13	--	X	Most recent and detailed work
Current Research	7	X	X	Adopted Marco et al. (1994) and Lee et al. (2001)

Based on our review, we deem the definition by CRR (2013) to be complete and sufficiently detailed, not only because it is the most recent from an organization of authority, but also because the strategy compilation was built on prior works, and incorporates the advantages and disadvantages for each EOL option. However, the CRR definition is contingent upon product characteristic summarization and it lacks numerical representation; therefore, it is appropriate only for qualitative analysis. However, with the support of the Lee et al. (2001)'s calculation formula, the definitions offered by Marco et al. (1994) become appropriate in that they can be used in quantitative analysis, despite comparative age of the original publication. Hence, the seven-factor EOL strategy presented by Marco et al. (1994) is adopted for integration to the comprehensive framework that is proposed in this paper.

Identification of an appropriate EOL strategy for each product component is also a complex step. Several studies have provided evaluation criteria/scenarios for such strategy selection cases. In one widely noted one, Keeney and Raiffa (1976) posited five rules for criteria selection:

- Completeness: all important points of view are covered;
- Non-redundancy: two or more criteria should not measure the same thing;
- Minimality: the dimension of the problem should be kept to a minimum;
- Operationality: the set of criteria can be measured and meaningfully used in the analysis; and
- Discrimination ability: the criteria should discriminate between alternatives: if all alternatives have the same value on a certain criterion, then that criterion will not play a role in the comparison of alternatives.

Krikke et al. (1998) identified three categories affecting EOL strategies: technical factors, legal factors, and economic factors. Lee et al. (2001) proposed seven strategies for components based on materials, such as recommending primary recycling for pure metal, secondary recycling for an alloy, and secondary recycling or landfill for a ceramic component. Rose (2001) identified five groups of evaluation characteristics, including external factors, material, disassembly, disassembly continued, and an inverse supply chain. Mangun and Thurston (2002) proposed four criteria, including product structure, cost and environmental impact, reliability of each component, and customer preferences. Bufardi et al. (2004) explored three criteria: direction of preference, scale of measurement, and unit of measurement. Teunter (2006) presented three groups of disassembly evaluation scenarios: a disassembly tree/graph, a process-dependent quality distribution, and a quality-dependent recovery option. Li et al. (2008) recommended five criteria for evaluation: component classification, life cycle span, recycling methods, material compatibility, and special handling and material classification. Ziout et al. (2013) described levels of evaluation criteria from four views of sustainability: the engineering view, the environmental view, the societal view, and the business view. Ma and Kremer (2015) developed an EOL decision-making approach using the evaluation criteria of social sustainability, environmental sustainability, economic sustainability, and designer's preferences. All of the above cited studies can be summarized with regards to the use of various aspects during evaluation as provided in Table 2.

Table 2 EOL Determination Criteria/Scenario Literature Summary

Author/Year	# of EOL Determination Scenario	Evaluation Aspect				Uncertain EOL Strategy	Uncertainty Handling Approach
		Material	Component Quality	Function/Module Complexity	External		
Keeney and Raiffa, 1976	5	--	--	--	--	--	--
Kikke et al., 1998	3	X	--	X	--	--	--
Lee et al., 2001	7	X	--	X	--	--	--
Rose, 2001	5	X	X	X	--	--	--
Mangun and Thurston, 2002	4	--	X	X	X	--	--
Hula et al., 2003	2	--	X	X	X	--	--
Bufardi et al., 2004	3	--	X	X	--	--	--
Gao et al., 2004	3	X	--	X	--	X	Fuzzy Reasoning PETRI Nets
Teunter, 2006	3	--	X	X	--	--	--
Li et al., 2008	5	X	X	X	--	--	--
Huang et al., 2010	3	X	--	X	X	X	Entropy Method
Behdad et al., 2012	2	--	--	X	X	X	Stochastic Programming
Ziout et al., 2013	4	--	X	X	X	--	--
Ma and Kremer, 2015	4	--	X	X	X	--	--

Current Research	4	X	X	X	X	X	Fuzzy Logic

The uncertainty in EOL strategy determination comes from the expert's vague and incomplete information-based judgement. As human beings, experts are said to be sources of two different types of uncertainty: aleatory and epistemic or subjective uncertainty (Ye et al., 2015). Aleatory uncertainty refers to irreducible uncertainty that is connected to the way brain processes information (Dror et al., 2006); while epistemic uncertainty is incomplete information with regards to component/product characteristics or the environment (Oberkempf et al., 2001). Epistemic uncertainty is reducible, and thus several works focused on ways to appropriately deal with this type of uncertainty. Two types of works are commonly used to handle epistemic uncertainty: probability based approaches and fuzzy logic based methodologies. Probability based approaches formulate the uncertainty with unknown parameters and utilize probability distribution to estimate unknown parameters to solve the problem. Huang et al. (2010) proposed an "entropy" approach based on discrete probability analysis of given product data distribution to capture the unreliability features of material selection. Behdad et al. (2012) developed a stochastic programming based uncertainty handling approach to link the uncertain customer return with EOL determination. Fuzzy logic based methods use "degree of trust" rather than simple "true or false" Boolean logic to model uncertainty. Gao et al. (2004) presented a fuzzy reasoning petri nets (FRPN) method to determine the optimal disassembly process. Through the state of the art comparison of several uncertainty handling methods (i.e., subjective probability theory, imprecise probability theory, evidence (Dempster-Shafer) theory, possibility theory), Ye et al. (2015) stated that fuzzy logic based approaches have many advantages over other approaches in intelligent decision making fields.

Given the above literature review on criteria selection, it is evident that an EOL strategy determination needs to consider many disparate aspects. The evaluation should cover potential impacts considering all components. Therefore, the evaluation framework should involve a comprehensive assessment ranging from internal to external factors that cover: 1) the influence of component internal aspects (e.g., material); 2) the component itself (e.g., component quality), addressing such features as component repair complexity; 3) the relationships among components' internal aspects to the product (function/module complexity), such as disassembly force; and 4) the factors external to the product (external), such as a succedaneum's price. No previously published paper addresses these four aspects; this study's consideration of these EOL determination criteria will bridge this literature gap.

With the identification of EOL strategy selection criteria, integrating them into the decision-making process becomes necessary. One widely used analysis method is multi-criteria decision making (MCDM) (e.g., Bufardi et al. 2004; Remery et al. 2012). The stream of related research adopts MCDM methods to balance multiple design criteria and reach a compromising EOL strategy. MCDM methods suit the nature of EOL management problems with regard to inclusiveness and comprehensiveness. The second set of widely used methods involves applying mathematical optimization algorithms to identify optimal EOL strategies (e.g., Erdos et al. 2001). However, such qualitative and quantitative methods for determining appropriate EOL strategies suffer from vagueness due either to the use of incomplete data sets or to the unavailability of data expressed in exact numbers (Yang and Li 2002). This makes the practical use of both MCDM methods and mathematical optimization algorithms questionable. For that reason, linguistic assessment has been proposed instead of a methodology requiring exact data (Beach et al. 2000). Fuzzy numbers and membership functions are widely used in representing linguistic expressions. To overcome the ambiguity in linguistic assessment, triangular and trapezoidal membership functions can be developed (Delgado et al. 1993). These membership functions can then be used to transform the linguistic variables into fuzzy numbers (Singh et al. 2006). Therefore, fuzzy logic is employed to handle uncertain EOL strategies in the proposed methodology.

3. Methodology

We present a comprehensive method to evaluate uncertain component End-of-Life (EOL) options during the product design stage using fuzzy logic. In the framework, three values are used to represent sustainability—cost, environmental impact, and labor time—corresponding to the economic, environmental and social aspects of sustainability. Environmental impact (EI) is an indicator which is generated using Eco-indicator 99 software to represent environmental sustainability. Positive impact is the adverse impact inflicted on the environment while the negative impact is averted (Ma and Kremer 2015). Once the expected value is obtained, a Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is implemented to identify specific EOL strategy for each component/product. Figure 1 presents the flow chart of this method.

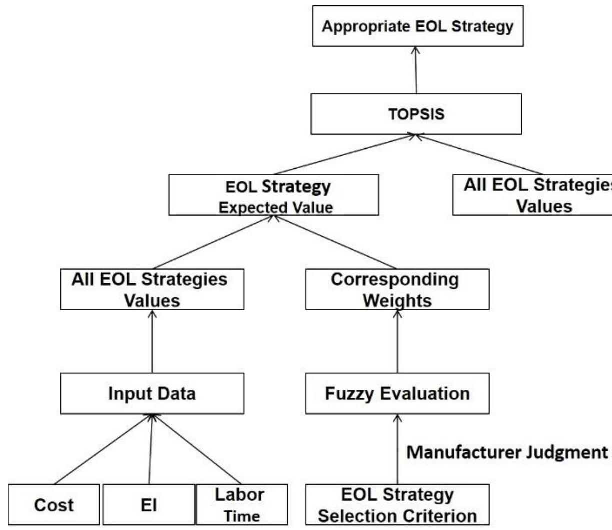

Figure 1 Method Flow Chart

3.1 EOL Strategy

As noted in the literature review section, the definition provided by Marco et al. (1994) is acceptable for use in that EOL strategies and can be quantified according to the calculation formula offered by Lee et al. (2001). An EOL strategy Ricoh comet diagram is shown in Figure 2. The EOL strategy definitions and corresponding cost calculation formulae are listed in Table 3.

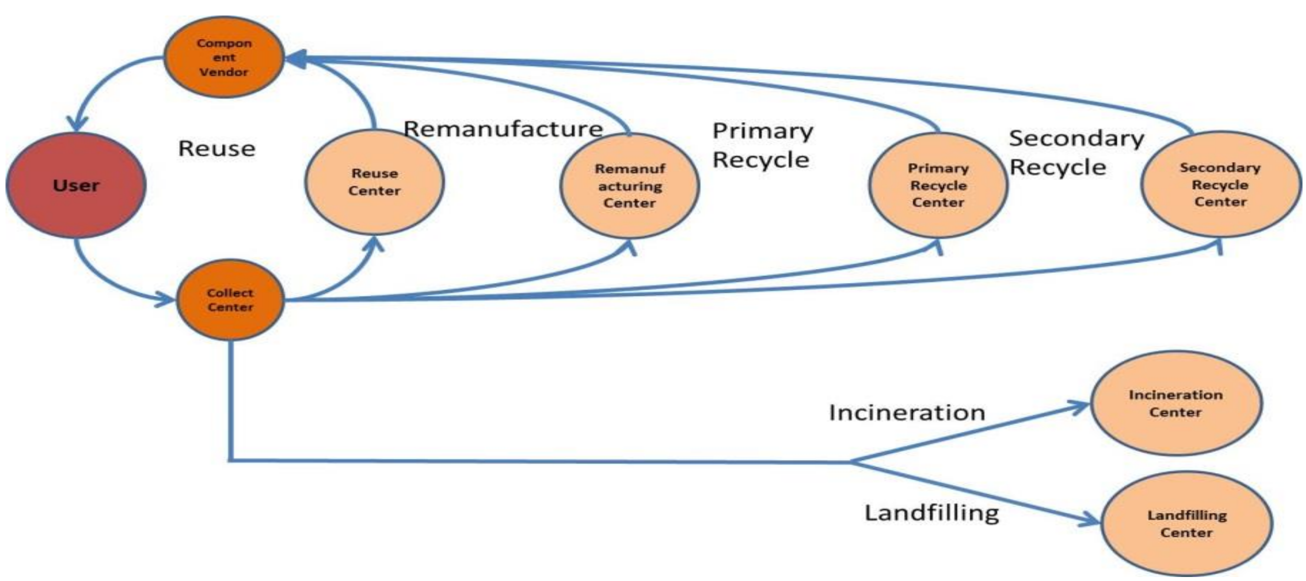

Figure 2 EOL Strategy Ricoh Comet Diagram (Adapted from Ma and Kremer 2015)

Table 3 EOL Option Definition and Corresponding Cost Formula

EOL Options	Definition (Marco et al. 1994)	Formula (Lee et al. 2001)
Reuse	Using in the same (direct reuse) or another (indirect reuse) application.	Cost of component –Miscellaneous cost
Remanufacture	Retaining serviceable parts, refurbishing usable parts; replacing identical or reworked components from obsolete products.	Cost of component -Miscellaneous cost
Primary Recycle	Reprocessing a material into a form that can be used in the same or another "high" value product.	(Weight of component * Market value of material) - Miscellaneous cost

Secondary Recycle	Reprocessing a material into a "low" value product.	(Weight of component * Scrap value of material) - Miscellaneous cost
Incinerated	Incinerating a material to produce heat and electricity.	(Energy produced * Unit cost of energy)-Miscellaneous cost
Landfills	Landfilling waste products with no intrinsic value.	-(Weight of component * Cost of landfill)- Miscellaneous cost
Special Handling	Mandatory for all toxic or hazardous materials.	-(Weight of component * Cost of special handling) – Miscellaneous cost
		Miscellaneous Cost= Collection Cost +Processing Cost

3.2 EOL Strategy Evaluation Criteria

Also as noted in the literature review, EOL strategy evaluation criteria involve four levels, ranging from the component-internal perspective to the product-external perspective. Figure 3 uses an archery target diagram to represent these four levels of evaluation criteria. Figure 4 shows the hierarchy table of all criteria, including these four levels and relevant 14 criteria.

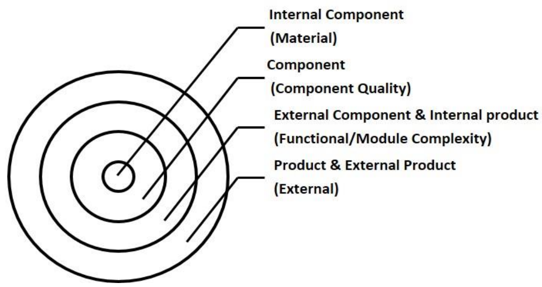

Figure 3 EOL Strategy Evaluation Criteria Archery Target Diagram (Adapted from Ma and Kremer 2016b)

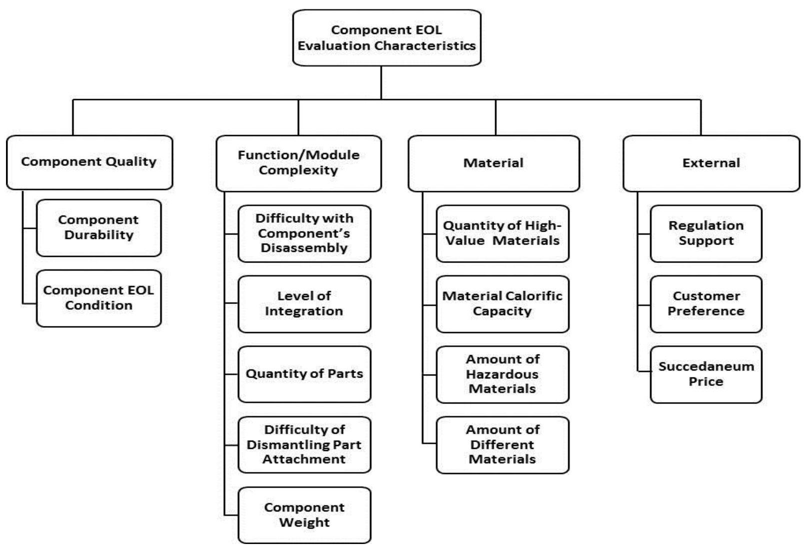

Figure 4 EOL Strategy Evaluation Criteria Hierarchy Table (Adapted from Ma and Kremer 2016b)

The proposed 14 criteria are introduced and explained below, adapting and justifying findings from Remery et al. (2012) with necessary extensions:

Component Durability: A component's residual value after it is first used, and defined as the ratio between the component's wear-out life and the product's useful life. This ratio should be as high as possible, indicating that the component retains function after the product's EOL and can be reused.

Component EOL Condition: The state of the component at the EOL of the product. The EOL condition is associated with the component's reliability and the circumstances in which it was used during its lifetime. It indicates the possibilities for reuse and the potential remanufacturing cost, environmental impact, and labor time required.

Difficulty with the Component's Disassembly: Takes into account the overall access to the component, as well as the number and type of attachments that must be dismantled to dissociate them from the product. This is directly related to the component's disassembly cost, environmental impact, and labor time used.

Level of Integration: Linked to the number of functions realized by a component and represents its complexity. The higher the number of functions performed by component, the greater will be the level of integration. The characteristics are used when determining the remanufacturing sustainability values.

Quantity of Parts: Defined as the in-dissociable elements of the component that perform one or more functions, except for the connection function. Generally, the quantity of parts is an indication of the component's disassembly cost, environmental impact, and labor time used, and therefore is related to sustainability values of remanufacturing and primary recycle.

Difficulty of Dismantling Part Attachments: Refers to the sustainability values of dismantling the connectors that link the various parts of the component. This parameter is involved in a component's part disassembly sustainability values, taken into account in remanufacturing and primary recycling in terms of social sustainability.

Component Weight: Influences landfill and incineration.

Quantity of High Value Materials: Indication of materials that can be resold at a high price after recovery. Materials with a very high value, like gold, palladium, and silver, are considered precious materials. Components made with these materials are usually designated as primary recycle. Other materials that can easily be resold are special metallic alloys (e.g., copper, aeronautic aluminum, iron), certain plastics (e.g., PEE, PC, PM, ABS), and glass.

Material Calorific Capacity: When this value is high, it is preferable to incinerate the component rather than dispose of it in a landfill because this permits the recovery of a substantial amount of energy. Generally, when calorific capacity is higher than 8 MJ/kg, the option of incineration is preferred over landfill disposal.

Amount of Hazardous Materials: Governed by laws and regulations that differ from one country to another. Generally, regulations stipulate that any hazardous component must be disassembled and it parts treated separately.

Amount of Different Materials: A component with few materials can be easily recycled since its treatment will require less separation effort. An important benefit, with an appropriate separation method, is that a significant amount of particular materials may be recovered and resold.

Regulation Support: A component with special materials will require either primary or secondary recycling, since specific regulations typically target environment protection considerations.

Customer Preference: This is positively related to the component economic performance, indicating that such a component will always be reused because of customer preference.

Succedaneum Price: This characteristic is negatively related to component economic performance. The higher the succedaneum price is, the lower the reuse rate of the component.

3.3 Fuzzy Evaluation

Fuzzy logic provides a technical basis to evaluate and derive an approximate conclusion (Yang and Li 2002), and therefore, it has been used widely where uncertain values need to be taken into account. One of these works (Ye et al. 2015) showed that in comparison to several other methods of uncertainty representation (i.e., subjective probability theory, imprecise probability theory, evidence (Dempster-Shafer) theory, possibility theory), fuzzy set theory has many advantages.

Fuzzy variables can be linguistic variables (Beach 2000). In this study, the EOL strategy evaluation criteria are assessed using a rating scale involving five levels: "very poor/very low", "poor/low", "fair/moderate", "good/high" and "very good/very high". The uncertainties of fuzzy numbers are represented using membership functions. Widely used membership functions include triangular and trapezoidal membership functions (Bufardi et al. 2004). The advantages of triangular membership functions are their simplicity; they have been commonly used in product development analysis (Delgado 1993; Singh et al. 2006). This study evaluates all EOL criteria and their weights to obtain each EOL strategy's score. The linguistic variable levels and corresponding fuzzy numbers are shown in Table 4.

Table 4 Linguistic Variable Level and Corresponding Fuzzy Set

EOL Evaluation Criteria Score (0~10)		Weight (0~1)	
Linguistic Variable Level	Fuzzy Set	Linguistic Variable Level	Fuzzy Set
Very Poor	(0, 1.5, 3)	Very Low	(0, 0.15, 0.3)
Poor	(2, 4, 6)	Low	(0.2, 0.4, 0.6)
Fair	(4, 5.5, 7)	Moderate	(0.4, 0.55, 0.7)
Good	(6, 7.5, 9)	High	(0.6, 0.75, 0.9)
Very Good	(8, 9, 10)	Very High	(0.8, 0.9, 1)

For each component, evaluation criteria for every EOL strategy (e.g., reuse, remanufacture) was assessed using a fuzzy linguistic variable from Table 4. The assessment was conducted via a survey of experts. Using component A as an example, the evaluation criterion was component durability, and the EOL strategy was reuse. The corresponding question for the expert was, “How do you evaluate component A’s component durability performance with respect to EOL strategy of reuse?” The expert’s answer to this question follows: “If component A’s duration is long, it is good for the reuse strategy”; thus, the component duration is “very high” and the corresponding fuzzy set is (8, 9, 10). Using this method, all evaluation criteria for all EOL strategies with respect to all components were assessed.

3.4 Weight Determination

Weight determination is important in multi-criteria decision processes. The weight of each EOL strategy for a specific component is derived from the integration of fuzzy evaluation, fuzzy operations, and the left-right fuzzy method, as well as normalization. The fuzzy evaluation was conducted in the previous procedural step; thus, this section explains the remaining three steps. Figure 5 presents the detailed process of weight determination.

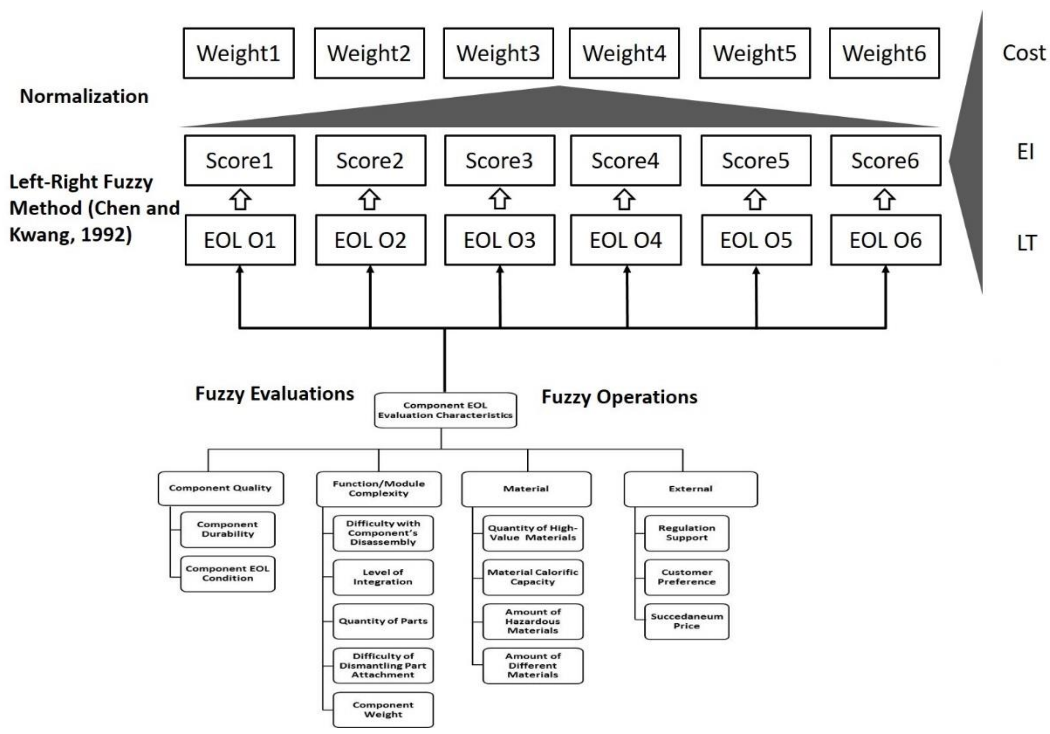

Figure 5 Weight Determination Flow Chart

3.4.1 Fuzzy Operations

Fuzzy evaluation generates hundreds of fuzzy sets, and an integrative method is needed to combine and simplify them. Here we adopt fuzzy arithmetic methods, and provide the α-cut method as described by Dutta et al. (2011) as follows:

$a = (a_1, a_2, a_3)$ $b = (b_1, b_2, b_3)$ are two fuzzy sets with following triangular membership functions:

$$\mu_a(x) = \begin{cases} \frac{x-a_1}{a_2-a_1}, & a_1 \leq x \leq a_2 \\ \frac{a_3-x}{a_3-a_2}, & a_2 \leq x \leq a_3 \end{cases} \tag{1}$$

$$\mu_b(x) = \begin{cases} \frac{x-b_1}{b_2-b_1}, & b_1 \leq x \leq b_2 \\ \frac{b_3-x}{b_3-b_2}, & b_2 \leq x \leq b_3 \end{cases} \tag{2}$$

Then α-cut of fuzzy numbers a and b will be presented as in the following:

$$a^\alpha = [(a_2 - a_1)\alpha + a_1, a_3 - (a_3 - a_2)\alpha] \tag{3}$$

$$b^\alpha = [(b_2 - b_1)\alpha + b_1, b_3 - (b_3 - b_2)\alpha] \tag{4}$$

The fuzzy number operations will be derived as:

$$a^\alpha + b^\alpha = [a_1 + b_1 + (a_2 - a_1 + b_2 - b_1)\alpha,\ a_3 + b_3 - (a_3 - a_2 + b_3 - b_2)\alpha] \tag{5}$$

$$a^\alpha - b^\alpha = [a_1 - b_3 + (a_2 - a_1 + b_3 - b_2)\alpha,\ a_3 - b_1 - (a_3 - a_2 + b_2 - b_1)\alpha] \tag{6}$$

$$a^\alpha \times b^\alpha = [((a_2 - a_1)\alpha + a_1) \times ((b_2 - b_1)\alpha + b_1), (a_3 - (a_3 - a_2)\alpha) \times (b_3 - (b_3 - b_2)\alpha)]$$
(7)

$$\frac{a^\alpha}{b^\alpha} = [\frac{(a_2-a_1)\alpha+a_1}{b_3-(b_3-b_2)\alpha}, \frac{a_3-(a_3-a_2)\alpha}{(b_2-b_1)\alpha+b_1}] \tag{8}$$

3.4.2 Left-Right Fuzzy Method

Fuzzy operations facilitate the combination of many fuzzy sets into a limited number of fuzzy sets. However, it is somewhat complicated to make relevant decisions due to uncertainty. Chen and Hwang (1992) developed a left and right boundary method to convert fuzzy sets into a single number, which makes decision making more straightforward. In this method, fuzzy maximizing and minimizing sets are defined to defuzzify a fuzzy number, respectively.

$$f_{max}(x) = \begin{cases} x, & 0 \leq x \leq 10, \\ 0, & otherwise \end{cases} \tag{9}$$

$$f_{min}(x) = \begin{cases} 10 - x, & 0 \leq x \leq 10, \\ 0, & otherwise \end{cases} \tag{10}$$

When given a triangular fuzzy number FPII defined as $f_{FPII}: R \rightarrow [0,10]$, with a triangular membership function, the right and left scores of FPII can be obtained, respectively, as

$$U_R(FPII) = sup_x[f_{FPII}(x) \wedge f_{max}(x)] \tag{11}$$

$$U_L(FPII) = sup_x[f_{FPII}(x) \wedge f_{min}(x)] \tag{12}$$

The total score of FPII can be obtained by combining the left and right scores. The total score of FPII is then used to determine the fuzzy number ranking, which is defined as:

$$U_T(FPII) = [U_R(FPII) + 10 - U_L(FPII)]/2 \tag{13}$$

For example, fuzzy set (0.2, 0.23, 0.5) is converted to a single number 0.35 by using the left-right method; this number can be used to represent the fuzzy set and rank (Ma and Kremer 2015). The single numbers will be normalized in order to obtain weights.

3.4.3 Weight Normalization

The normalization is the final step to determine weight for each EOL strategy. The idea is finding the proportion of specific EOL strategy in all EOL strategies. The following Eq. 14 is used to find the normalized weight.

$$w_i = \frac{s_i}{\sum_1^6 s_i} \tag{14}$$

Where S_i is crisp score from Eq. 13, which corresponds to EOL strategy. Because there are six EOL strategies, i is from 1 to 6.

3.5 TOPSIS Method

TOPSIS method is one of the most widely used MCDM methods because it considers both positive-ideal (best) and negative-ideal (worst) in the process (Boran et al. 2009). Suppose the MCDM problem has n alternatives, $A_1, A_2, \dots\ A_n$ and m decision criteria, $C_1, C_2, \dots\ C_m$. Decision criteria is used to assess each alternative. All evaluations form a decision matrix denoted as $X = (x_{ij})_{n\times m}$. Weight $W = (w_1, w_2, \dots, w_m)$ are used to represent relative criteria. According to Boran et al. (2009), TOPSIS method can be summarized in five steps:

1) Normalize the decision matrix by equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{n} x_{ij}^2}}, i = 1,2,3, \dots, n; j = 1,2,3, \dots, m \quad (15)$$

Each item x_{ij} in decision matrix X will be transferred to r_{ij} in the new decision matrix R.

2) Obtain the weighted decision matrix through equation:

$$v_{ij} = w_j r_{ij}, , i = 1,2,3, \dots, n; j = 1,2,3, \dots, m \quad (16)$$

3) Identify positive ideal solution and negative ideal solution by following equations:

Positive ideal solution: $S^+ = \{v_1^+, v_2^+, \dots, v_m^+\} = \left\{\left(\max_j r_{ij} \mid j \in M^+\right), \left(\min_j r_{ij} \mid j \in M^-\right)\right\}$ (17)

Negative ideal solution: $S^- = \{v_1^-, v_2^-, \dots, v_m^-\} = \left\{\left(\min_j r_{ij} \mid j \in M^+\right), \left(\max_j r_{ij} \mid j \in M^-\right)\right\}$ (18)

M^+ and M^- are the sets of criteria with maximum objectives and minimum objectives, respectively.

4) Calculate the Euclidean distances of each alternative from both positive ideal solution and negative ideal solution using following equations:

$$ED_i^+ = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_j^+)^2}, i = 1,2,3, \dots, n \quad (19)$$

$$ED_i^- = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_j^-)^2}, i = 1,2,3, \dots, n \quad (20)$$

5) Calculate the closeness of each alternative to the positive ideal solution using equation;

$$RC_i = \frac{ED_i^-}{ED_i^- + ED_i^+}, \ i = 1,2,3, \dots, n \quad (21)$$

The most appropriate solution will be the alternative with highest RC_i.

In this study, the positive ideal solution in the TOPSIS is replaced by the expected value obtained from previous steps. The purpose is searching the alternative with closest value to the expected value and identify it as most appropriate strategy for component/product.

The methodology implements fuzzy logic to handle uncertainty in EOL option decision making. The uncertain expert estimation information in the format of linguistic terms is collected from decision makers. By using Table 4, the linguistic terms are transferred to multiple fuzzy numbers. Fuzzy operations shown in Eq. 1 ~ 8 aggregate multiple fuzzy numbers into a fuzzy number; the left-right fuzzy method is then adopted to convert this fuzzy number into a single crisp number through Eq. 9 ~ 13. As explained thus far, decision maker's estimates are incorporated in a way that is easy for the human decision maker to present judgments, and that where the uncertainty of estimates is reduced through conversion to crisp numbers. Combined with given cost, environmental impact and labor time, TOPSIS approach in Eq. 15 ~ 21 derives the appropriate EOL strategy for each product component.

4. Case Study

A refrigerator is used to show the implementation of the proposed methodology. The refrigerator is composed of twenty components, and each component interacts with other components to generate primary product functions. Each component has its own attributes, such as material, cost, and price. The product data set of the refrigerator is derived from Chung et al. (2012) and is supplemented by data from websites providing product material market price, scrap price, and landfill price: rivcowm.org, alibaba.com, earthworksrecycling.com, recycleinme.com, recycle.net. Figure 6 presents a refrigerator dissection sketch. The refrigerator components only include the main parts. Certain small connectors, such as fasteners and screw bolts, are excluded from this case study. Table 5 summarizes the EOL strategy cost for components. The environmental impact and labor time used data are provided in Appendix Tables A and B. In order to calculate the expected value, further assumptions are made as follows:

- Collection cost, environmental impact and labor time are not considered;
- Processing cost/environmental impact/labor time for reuse, remanufacture and recycle are 20%, 40%, 60% (respectively) of the manufacturing cost;
- The retired refrigerator is not damaged, which means there is no weight loss for any component;
- Copper, glass, and steel components cannot use incineration as an EOL strategy.

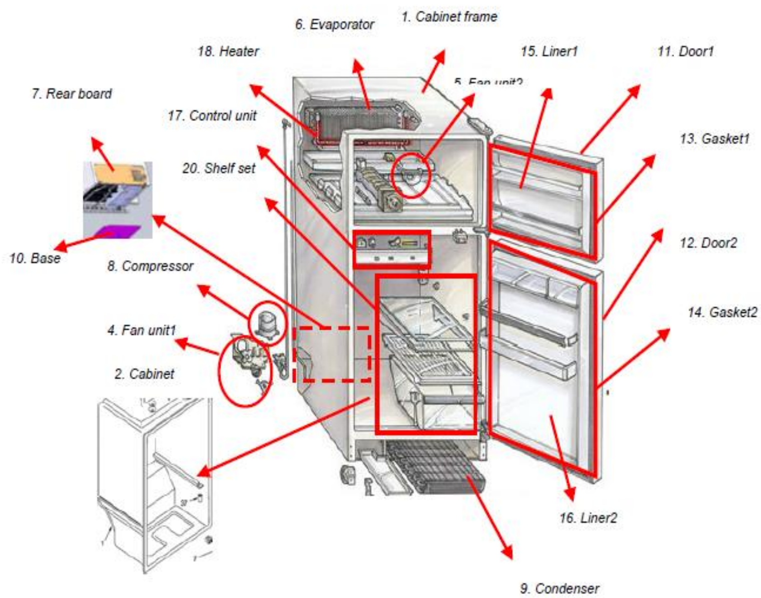

Figure 6 Refrigerator Sketch (adopted from Chung et al. 2012)

Table 5 Refrigerator Component EOL Strategy Cost

No.	Component	Reuse	Remanufacture	Primary Recycle	Secondary Recycle	Incineration	Landfill
1	Cabinet Frame	180	170	21.34	20.82	0	0.94
2	Cabinet	0	0	23.45	21.25	2.08	1.17
3	Duct in Room	0	0	0.82	0.75	0.07	0.04
4	Fan Unit 1	0	0	0.43	0.43	0	0.02
5	Fan Unit 2	0	0	0.43	0.43	0	0.02
6	Evaporator	50	42	0.80	0.64	0	0.02
7	Rear Board	27	23	0.89	0.87	0	0.04
8	Compressor	80	71	7.19	7.04	0	0.32
9	Condenser	40	30	2.40	2.35	0	0.11
10	Base	26	19	1.12	1.09	0	0.05
11	Door 1	60	51	2.42	2.38	0	0.11
12	Door 2	70	59	3.90	3.82	0	0.17
13	Gasket 1	0	0	0.03	0.03	0.0028	0.00
14	Gasket 2	0	0	0.05	0.04	0.0043	0.00
15	Door Liner 1	0	0	1.79	1.62	0.16	0.09
16	Door Liner 2	0	0	3.74	3.24	0.32	0.18
17	Control Unit	332	317	3.98	3.75	0.16	0.19
18	Heater	0	0	0.17	0.13	0	0.00
19	Dryer	13	10	0.67	0.59	0	0.00
20	Shelf Set	0	0	1.01	0.92	0.09	0.05

In order to simplify the calculations, the weight for each EOL strategy evaluation criteria is set as "moderate", which is (0.4, 0.55, 0.7). The EOL strategy criteria evaluation are presented in Appendix Table C. By following fuzzy operations Eqs. 1-8 listed in Section 3.4.1, computations are completed to provide each component with a fuzzy set to represent cost, environmental impact, and labor time. Eqs. 9-13 of left-right fuzzy method then are applied to defuzzify these fuzzy sets into single numbers. Normalization of these single numbers will generate corresponding weights through Eq. 14. Table 6 shows the calculations for the cabinet frame. The first four rows represent fuzzy operations' results; the middle four rows show left-right method's results; and last four rows present the normalized weights' results.

Table 6 Cabinet Frame Weight Determination

Fuzzy Operations	Reuse (A_1)	Remanufacturing (A_2)	Primary Recycle (A_3)	Secondary Recycle (A_4)	Incinerate (A_5)	Landfill (A_6)
Cost	(2.66,8.66,20)	(5, 7.5, 10)	(0,2.5,5)	(0,1.25,4.875)	(5,7.5,10)	(0, 0, 2.5)
Environmental Impact	(7.5, 10, 10)	(5, 7.5, 10)	(6.25,25, 56.25)	(0, 12.5, 37.5)	(0,0,0.9)	(0, 0, 0.45)
Labor Time	(7.5,10,10)	(0.75,1.33,2)	(6.875,9.375,10)	(5,7.5,10)	(0, 0, 2.5)	(0, 0, 2.5)
Left-Right Method	**Reuse (A_1)**	**Remanufacturing (A_2)**	**Primary Recycle (A_3)**	**Secondary Recycle (A_4)**	**Incinerate (A_5)**	**Landfill (A_6)**
Cost	5.56	5.2	4.8	4.18	5.2	5.1
Environmental Impact	4.75	5.2	5.77	5.37	5.01	5.01
Labor Time	4.75	4.62	4.72	5.2	5.1	5.1
Normalization	**Reuse (A_1)**	**Remanufacturing (A_2)**	**Primary Recycle (A_3)**	**Secondary Recycle (A_4)**	**Incinerate (A_5)**	**Landfill (A_6)**
Cost	0.19	0.17	0.16	0.14	0.17	0.17
Environmental Impact	0.15	0.17	0.19	0.17	0.16	0.16
Labor Time	0.16	0.16	0.16	0.18	0.17	0.17

Considering the cost weight result in Table 6 and the actual cost of cabinet frame in Table 5, the expected cost of cabinet frame in EOL stage is calculated as:

$$180 \times 0.19 + 170 \times 0.17 + 21.34 \times 0.16 + 20.82 \times 0.14 + 0 \times 0.17 + 0.94 \times 0.17 = \$69.59$$

Similarly, calculations were completed to identify the EOL expected values of the additional components. Table 7 summarizes all computed values.

Table 7 Refrigerator Components Expected EOL Values

Component	Cost ($)	Environmental Impact (mPt)	Labor Time (s)
Cabinet Frame	69.59	-431.75	1252.63
Cabinet	7.3	-2009.41	196.91
Duct in Room	0.25	-72.22	7.26
Fan Unit 1	0.16	-9.74	3.11
Fan Unit 2	0.14	-11.29	3.14
Evaporator	15.8	-119.27	28.95
Rear Board	8.75	-16.47	54.74
Compressor	27.77	-141.26	424.18
Condenser	12.86	-49.58	129.35
Base	7.67	-22.06	68.03
Door 1	19.45	-49.18	143.64
Door 2	23.12	-73.13	232.31
Gasket 1	0.01	-2.14	0.27
Gasket 2	0.02	-3	0.39
Door Liner 1	0.6	-160.03	15.69
Door Liner 2	1.23	-315.38	30.05
Control Unit	106.7	-206.2	252.99
Heater	0.04	-25.7	0.78
Dryer	4.09	-1.69	5.98
Shelf Set	0.33	-74.65	8.38

When the expected values are obtained, TOPSIS is implemented to identify the most appropriate strategy. Three sustainability dimensions serve as decision criteria; and seven feasible EOL strategies are the considered alternatives. The expected values in Table 7 are used as positive ideal solutions after normalization in the TOPSIS. For example, the three sustainability values of cabinet frame are $69.59, -431.75mPt and 1252.63s; after normalization, these values are transferred as 0.2688, -0.1846 and 0.2475, which will be employed as positive ideal solution for cabinet EOL strategy decision making. Equal weights are used for three decision criteria. By using Eqs. 15-21, the appropriate EOL strategy for each component is obtained. Table 8 summarizes positive ideal solution and negative ideal solution with respect to all refrigerator components. Table 9 lists relevant closeness of TOPSIS with respect to each alternative, and also identifies most appropriate EOL strategy for each component.

Table 8 Positive Ideal Solution and Negative Ideal Solution

Component	Positive Ideal Solution			Negative Ideal Solution		
	Cost	Environmental Impact	Labor Time	Cost	Environmental Impact	Labor Time
Cabinet Frame	0.2688	-0.1846	0.2475	0	0.3028	0
Cabinet	0.2242	-0.2592	0.2252	0	0.01475	0
Duct in Room	0.2189	-0.2498	0.2362	0	0.01387	0
Fan Unit 1	0.2543	-0.2136	0.2164	0	0.01491	0
Fan Unit 2	0.2242	-0.2457	0.2183	0	0.01480	0
Evaporator	0.2351	-0.2369	0.2472	0	0.07609	0
Rear Board	0.2394	-0.1799	0.2440	0	0.3231	0
Compressor	0.2503	-0.1843	0.2487	0	0.3126	0
Condenser	0.2486	-0.1885	0.2548	0	0.3044	0
Base	0.2314	-0.1847	0.2501	0	0.3115	0
Door 1	0.2396	-0.1816	0.2476	0	0.2983	0
Door 2	0.2444	-0.1815	0.2478	0	0.3224	0
Gasket 1	0.2289	-0.2420	0.2259	0	0.01810	0
Gasket 2	0.2975	-0.2174	0.2180	0	0.01667	0
Door Liner 1	0.2405	-0.2582	0.2347	0	0.01407	0
Door Liner 2	0.2406	-0.2576	0.2253	0	0.01425	0
Control Unit	0.2264	-0.2470	0.2514	0.0003395	0.1003	0.003348
Heater	0.1837	-0.2403	0.2331	0	0.001496	0
Dryer	0.2416	-0.1724	0.2459	0	0.3398	0
Shelf Set	0.2342	-0.2491	0.2221	0	0.01649	0

Table 9 Refrigerator Component Relevant Closeness $\boldsymbol{RC}$ and Appropriate EOL Strategy

Component	Relevant Closeness RC						Appropriate EOL Strategy
	Reuse	Remanufacturing	Primary Recycle	Secondary Recycle	Incinerate	Landfill	
Cabinet Frame	0.6468	0.5549	0.6424	0.6457	0.4252	0.4123	Reuse
Cabinet	0.0347	0.0347	0.5883	0.6310	0.2574	0.1003	Secondary Recycle
Duct in Room	0.0329	0.0329	0.6898	0.6224	0.2460	0.0994	Primary Recycle
Fan Unit 1	0.0363	0.0363	0.5858	0.6194	0.0363	0.0971	Secondary Recycle
Fan Unit 2	0.0359	0.0359	0.6870	0.6192	0.0359	0.0963	Primary Recycle
Evaporator	0.5890	0.5817	0.5917	0.5914	0.1548	0.1528	Primary Recycle
Rear Board	0.6090	0.6461	0.6338	0.6320	0.4555	0.4408	Remanufacturing
Compressor	0.6104	0.5498	0.6609	0.6523	0.4399	0.4263	Primary Recycle
Condenser	0.5997	0.5478	0.6421	0.6453	0.4305	0.4169	Secondary Recycle
Base	0.6507	0.5461	0.6388	0.6485	0.4455	0.4311	Reuse
Door 1	0.6454	0.5512	0.6377	0.6370	0.4337	0.4197	Reuse
Door 2	0.6585	0.5470	0.6363	0.6546	0.4510	0.4367	Reuse
Gasket 1	0.0430	0.0430	0.5823	0.6356	0.2916	0.0590	Secondary Recycle
Gasket 2	0.0375	0.0375	0.5846	0.6731	0.2652	0.0498	Secondary Recycle
Door Liner 1	0.0321	0.0321	0.5932	0.5328	0.2433	0.0978	Primary Recycle
Door Liner 2	0.0329	0.0329	0.5905	0.5347	0.2464	0.0974	Primary Recycle
Control Unit	0.5885	0.5733	0.6046	0.6050	0.4061	0.1676	Secondary Recycle
Heater	0.0039	0.0039	0.5782	0.6195	0.0039	0.0609	Secondary Recycle
Dryer	0.6072	0.5438	0.6317	0.6642	0.4685	0.4527	Secondary Recycle
Shelf Set	0.0389	0.0389	0.6848	0.6421	0.2758	0.1000	Primary Recycle

The refrigerator components' EOL strategies presented in Table 9 show that reuse, remanufacturing, primary recycle and secondary recycle are the recommended strategies. The calculation process involves both qualitative and quantitative evaluations of EOL strategies from a comprehensive perspective. Fuzzy logic applied in this framework deals with uncertainties and provides operational support to obtain weights for each EOL strategy. TOPSIS method implemented in this approach helps select the most appropriate EOL strategy for each component.

Cradle-to-cradle is a sustainable development philosophy that has become widely accepted and applied across a great number of fields. Uncertainty exists in various perspectives of design that causes ineffectiveness and inefficiency during the product design stage, and accounting for product development decision making under uncertainty is an urgent need. In response, this research endeavored to handle the uncertainty of identifying an EOL strategy for a specific product component in the design stage through the use of expert judgments. A fuzzy logic based method is developed to factor in uncertainty due to expert estimation. The proposed methodology analyzes seven strategies (quantitative and qualitative) and generates three expected values to represent the EOL stage sustainability performance, assessable in the design stage. Moreover, this research recognizes the incompleteness of existing EOL strategy assessment criteria, and it introduces a comprehensive EOL evaluation framework to capture all strategic perspectives by summarizing 14 evaluation criteria that span from an internal component aspect to the external product itself. In addition, a modified TOPSIS method incorporates with obtained expected value to identify the most appropriate EOL strategy for product/component.

5. Conclusion and Future Work

The proposed methodology is designed to handle EOL strategy uncertainty in a comprehensive manner during the design stage. It is scientific and flexible, since the required input information covers all aspects of every component and evaluates them with the aid of fuzzy linguistic variables. Importantly, designers' perceptions are also involved in this methodology. The weight determination is subject to the designers' individual opinions and incorporated as fuzzy variables. The three expected values derived from this method can be used to support product development through (1) a product redesign; (2) handling appropriate end-of-life decisions for a retired product; or (3) product life cycle sustainability performance forecast and assessment. The approach can also be expanded to provide recommendations to product sustainability research.

Several drawbacks exist in the methodology. The proposed methodology requires substantial effort for data gathering and calculating. This effort is proportional to number of components in the product. For products with a large number of components, the data collection and analysis process is time-consuming. For the future studies in this method, a software designed to facilitate data collection and carry out the analysis through programmed algorithms will be involved that should significantly reduce the effort. Beyond that, the weight determination process relies on the fuzzy input of designers, which may result in inappropriate and subjective decision making. Future studies will include a greater number of designers in the weight determination and will apply a multi-person decision-making approach (MPDM) to obtain weights, thus broadening the reliability factor. As with the time involved to gather and calculate the data, the potential for utilizing a super computer and software could be an effective way to tackle the challenge. Moreover, some quantitative evaluation of criteria, such as “component EOL condition” and “component duration”, are important and should be involved in EOL decision making. Future research will develop a quantified evaluation model which involves all these factors in the decision-making framework. In addition, although this study only adopts 14 criteria, the proposed method can be extended with additional criteria; thus, additional criteria can be added, or new ones can be proposed to replace the existing ones. Finally, TOPSIS approach is sensitive to weights change. Future work will include a comprehensive sensitivity analysis study regarding to weights and final results.

References

1. Abudullah ZT, Shunsheng G, Buyun S (2015) Eco-design application to drive sustainable manufacturing. Advanced Science Letters. 21(12), 3610-3614.
2. Appelqvist P, Lehtonen, JM, Kokkonen, J (2004) Modeling in product and supply chain design: literature survey and case study. Journal of Manufacturing Technology Management, 15(7), 675-686.
3. Beach R, Muhlemann AP, Price DHR, Paterson A, Sharp JA (2000) A review of manufacturing flexibility. European Journal of Operational Research, 122(1), 41-57.
4. Behdad S, Williams AS, Thurston D (2012) End-of-life decision making with uncertain product return quality. Journal of Mechanical Design, 134(10), 10092.
5. Boran FE, Genc S, Kurt M, Akay D (2009) A multi-criteria intuitionistic fuzzy group decision making for supplier selection with TOPSIS method. Expert Systems with Applications, 36, 11363-11368.
6. Bryant CR, Sivaramakrishnan KL, Wie MV, Stone RB, McAdams DA (2004) A modular design approach to support sustainable design. Proceedings of DETC’04 ASME 2004 Design Engineering Technical Conference and Computers and Information in Engineering Conference, Salt Lake City, Utah.
7. Bufardi A, Gheorghe R, Kiritsis D, Xirouchakis P (2004) Multicriteria decision-aid approach for product end-of-life alternative selection. International Journal of Production Research, 42(16), 3139-3157.
8. Center for Remanufacturing and Reuse (2013) A description of the design for end-of-life process, http://www.remanufacturing.org.uk/pdf/story/1p295.pdf?session=RemanSession:807618970f36920117UiJ20B9285.
9. Chen SJ, Hwang CL (1992) Fuzzy Multiple Attribute Decision Making Methods and Application. Springer, Berlin, Heidelberg.
10. Chung WS (2012) A modular design approach to improve product life cycle performance based on optimized close loop supply chains. Ph.D. dissertation. Penn State University.
11. Chung WS, Okudan GE, Wysk RA (2011) A modular design approach to improve the life cycle performance derived from optimized closed-loop supply chain. Proceedings of the ASME 2011 International Design Engineering Technical Conference & Computers and Information in Engineering Conference: Washington, DC.
12. Chung WS, Kremer GEO, Wysk RA (2016) A dynamic programming method for product upgrade planning incorporating technology development and end-of-life decisions. Journal of Industrial and Production Engineering. 5, 1-12.
13. Delgado M, Verdegay JL, Vila V (1993) Linguistic decision making models. International Journal of Intelligent Systems, 7 (5), 479–492.
14. Dowlatshahi S (1992) Purchasing’s role in a concurrent engineering environment. International Journal of Purchasing Materials Management, 28(1), 21-25.
15. Dror I E, Charlton D (2006) Why Experts Make Errors. J. Forensic Ident., 56(4), 600–616.
16. Dutta P, Boruah H, Ali T (2011). Fuzzy arithmetic with and without using α-cut method: a comparative study. International Journal of Latest Trends in Computing, 2(1), 99-107.
17. Erdos G, Kis T, Xirouchakis P (2001) Modeling and evaluating product end-of-life options. International Journal of Production Research, 39(6), 1203-1220.
18. Gao MM, Zhou MC, Tang Y (2004). Intelligent decision making in disassembly process based on fuzzy reasoning Petri Nets. IEEE Transactions on Systems, Man, and Cybernetics-Part B: Cybernetics, 34(5), 2029-2034.

19. Hula A, Jalali K, Hamza K, Skerlos SJ, Saitou K (2003) Multi-criteria decision-making for optimization of product disassembly under multiple situations. Environ. Sci. Technol., 37(23), 5303-5313.
20. Huang HH, Zhang L, Liu ZF, Sutherland JW (2010) Multi-criteria decision making and uncertainty analysis for materials selection in environmentally conscious design. International Journal of Advanced Manufacturing Technology, 52(5), 421-432.
21. Ijomah W, Bennett JP, Pearce J (1999) Remanufacturing Evidence of Environmental Conscious Business Practice in UK. EcoDesign '99 First International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Published by IEEE Computer Society Piscataway NJ, Tokyo, Japan, 192-196.
22. Ishii K, Juengel C, Eubanks CF (1995) Design for product variety: Key to product line structuring. Proceedings of the 1995 ASME Design Engineering Technical Conferences, 7th International Conference on Design Theory and Methodology, Boston, MA.
23. Ji YJ, Chen XB, Qi GN, Song LW (2012) Modular design involving effectiveness of multiple phases for product life cycle. International Journal of Advanced Manufacturing Technology, pp. 1-14.
24. Keeney RL, Raiffa H (1976) Decisions with multiple objectives: preference and value tradeoffs. Chichester, Wiley.
25. Kikke HR, Harten AV, Schuur PC (1998) On a medium term of product recovery and disposal strategy for durable assembly products. International Journal of Production Research, 36(1), 111-139.
26. Kiritsis D, Bufardi A, Xirouuchakis P (2003) Multi-criteria decision aid for product end of life options selections. IEEE International Symposium on Electronics and the Environment, 48-53. DOI: 10.1109/ISEE.2003.1208046.
27. Kreng VB, Lee TP (2004a) Modular product design with grouping genetic algorithm: a case study. Computers and Industrial Engineering, 46(3), 443-460.
28. Kreng VB, Lee TP (2004b) QFD-Based modular product design with linear integer programming—A case study. Journal of Engineering Design, 15(3), 261-284.
29. Lai XX, Gershenson JK (2009) DSM-based product representation for retirement process-based modularity. Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, San Diego, CA, Aug30-Sep.2.
30. Lee SG, Lye SW, Khoo MK (2001) A multi-objective methodology for evaluating product end-of-life options and disassembly. International Journal of Advanced Manufacturing Technology, 18, 148-156.
31. Li JZ, Zhang HC, Gonzalez MA, Yu S (2008) A multi-objective fuzzy graph approach for modular formulation considering end of life issues. International Journal of Production Research, 46(14), 4011-4033.
32. Ma J, Kremer GE (2014a) A modular product design approach with key components consideration to improve sustainability. Proceedings of the ASME 2014 IDETC Conference, Buffalo, NY, Aug. 17-20.
33. Ma J, Kremer GE (2014b) A fuzzy logic-based approach for handling uncertain EOL options in product design stage. Proceedings of ISERC 2014 Conference, Montreal, QC, Canada, May 31-June 3.
34. Ma J, Kremer GE (2015) A fuzzy logic-based approach to determine product component end-of-life option from the views of sustainability and designer's perception. Journal of Cleaner Production, 108, 289-300.
35. Ma J, Kremer GE (2016a) A systematic literature review of modular product design (MPD) from the perspective of sustainability. International Journal of Advanced Manufacturing Technology. doi:10.1007/s00170-015-8290-9.
36. Ma J, Kremer GE (2016b) A sustainable modular product design approach with key components and uncertain end-of-life strategy consideration. International Journal of Advanced Manufacturing Technology. 85(1), 741-763.
37. Mangun D, Thurston DL (2002). Incorporating component reuse, remanufacture and recycle into product portfolio design. IEEE Transactions on Engineering Management, 49(4), 479-490.
38. Marco P, Eubanks CF, Ishii K (1994) Compatibility analysis of product design for recyclability and reuse. Proceedings of the 1994 ASME Computers in Engineering Conference.
39. Oberkampf WL, Helton JC, Sentz K (2001) Mathematical Representation of Uncertainty, American Institute of Aeronautics and Astronautics Non-Deterministic Approaches Forum, Seattle, WA.
40. Remery M, Mascle C, Agard B (2012) A new method for evaluating the best product end-of-life strategy during the early design phase. Journal of Engineering Design, 23(6), 419-441.
41. Rose CM (2001) Design for environment: a method for formulating product end-of-life strategies. Ph.D. dissertation, Stanford University.
42. Singh RK, Kumar S, Choudhury AK, Tiwari MK (2006) Lean tool selection in a die casting unit: a fuzzy-based decision support heuristic. International Journal of Production Research, 44(7), 1399-1429.
43. Stevels ALN (1997) Optimization of the End-of-Life System. Appears in Ecodesign: A Promising Approach, Brezet JC, van Hemel C (eds.), Paris, France, UNEP Working Group on Sustainable Product Development, 346.

44. Teunter RH (2006) Determining optimal disassembly and recovery strategies. International Journal of Management Science, 34, 533-537.
45. Walls M (2006) Extended Producer Responsibility and Product Design: Economic Theory and Selected Case Studies. Resources for the Future discussion paper 06-08.
46. Yan JH, Feng CH, Cheng K (2012) Sustainability-oriented product modular design using kernel-based fuzzy c-means clustering and genetic algorithm. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 226 (10), 1635-1647.
47. Yang SL, Li TF (2002) Agility evaluation of mass customization product manufacturing. Journal of Materials Processing Technology, 129 (1–3), 640–644.
48. Ye Y, Jankovic M, Okudan Kremer GE 2015. Integration of Expert Estimation Uncertainty into Supplier Identification, ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part P: Mechanical Systems, 1(3), 10.1115/1.4030463, 031005.
49. Ziout A, Azab A, Atwan M (2014) A holistic approach for decision on selection of end-of-life products recovery options. Journal of Cleaner Production, 65, 497-516.

Appendix

Table A Refrigerator Component EOL Strategy Environmental Impact (mPt)

No.	Component	Reuse	Remanufacture	Primary Recycle	Secondary Recycle	Incineration	Landfill
1	Cabinet Frame	0	708.18	-1652.42	-1432.15	0	33.05
2	Cabinet	0	0	-5862.6	-4621	-556.95	114.32
3	Duct in Room	0	0	-205.6	-189	-19.53	4.01
4	Fan Unit 1	0	0	-33.81	-29	0	0.68
5	Fan Unit 2	0	0	-33.81	-29	0	0.68
6	Evaporator	0	38.3	-383.04	-301.6	0	0.74
7	Rear Board	0	29.58	-69.02	-49.67	0	1.38
8	Compressor	0	239.55	-558.95	-444.16	0	11.18
9	Condenser	0	80.07	-186.83	-159.31	0	3.74
10	Base	0	37.2	-86.8	-69.7	0	1.74
11	Door 1	0	80.79	-188.51	-169.84	0	3.77
12	Door 2	0	129.93	-303.17	-219.6	0	6.06
13	Gasket 1	0	0	-8	-3	-0.76	0.16
14	Gasket 2	0	0	-12	-6	-1.14	0.23
15	Door Liner 1	0	0	-447.2	-395.63	-42.48	8.72
16	Door Liner 2	0	0	-894.4	-769.21	-84.97	17.44
17	Control Unit	0	83.72	-621	-498	-117.3	12.19
18	Heater	0	0	-80.64	-65.39	0	0.16
19	Dryer	0	3.33	-7.77	-4.66	0	0.16
20	Shelf Set	0	0	-253.2	-139.68	-24.05	4.94

Table B Refrigerator Component EOL Strategy Labor Time (s)

No.	Component	Reuse	Remanufacture	Primary Recycle	Secondary Recycle	Incineration	Landfill
1	Cabinet Frame	3400.51	3466.97	623.99	283.94	0	17.00
2	Cabinet	0	0	774.85	352.59	21.11	21.11
3	Duct in Room	0	0	27.17	12.37	0.74	0.74
4	Fan Unit 1	0	0	12.77	5.81	0	0.35
5	Fan Unit 2	0	0	12.77	5.81	0	0.35
6	Evaporator	76.64	82.23	14.06	6.40	0	0.38
7	Rear Board	142.04	162.31	26.06	11.86	0	0.71
8	Compressor	1150.26	1162.95	211.07	96.05	0	5.75
9	Condenser	384.48	295.32	70.55	32.10	0	1.92
10	Base	178.63	190.12	32.78	14.92	0	0.89
11	Door 1	387.93	399.01	71.19	32.39	0	1.94
12	Door 2	623.89	648.21	114.48	52.10	0	3.12
13	Gasket 1	0	0	1.06	0.48	0.03	0.03
14	Gasket 2	0	0	1.59	0.72	0.04	0.04
15	Door Liner 1	0	0	59.11	26.90	1.61	1.61
16	Door Liner 2	0	0	118.21	53.79	3.22	3.22
17	Control Unit	673.74	690.36	123.63	56.26	3.37	3.37
18	Heater	0	0	2.96	1.35	0	0.08
19	Dryer	15.99	17.01	2.93	1.34	0	0.08
20	Shelf Set	0	0	33.47	15.23	0.91	0.91

Table C Refrigerator Component Fuzzy Evaluation

	Cabinet Frame	Cabinet	Duct in Room	Fan Unit 1	Fan Unit 2	Evaporator	Rear Board	Compressor	Condenser	Base	Door 1	Door 2	Gasket 1	Gasket 2	Door Liner 1	Door Liner 2	Control Unit	Heater	Dryer	Shelf Set
Durability (N_1)	VG	VG	F	G	P	G	G	G	F	G	G	G	VG	G	F	G	G	F	G	P
EOL Condition (N_2)	G	G	F	F	VP	F	F	F	P	F	F	F	G	F	P	F	F	F	F	VP
Quantity of High-Value Materials (N_3)	P	P	P	F	P	F	F	F	F	G	F	F	P	F	F	F	G	P	F	P
Calorific Capacity (N_4)	G	G	G	P	G	P	P	F	P	F	F	P	G	P	P	P	F	G	P	G
Difficulty with the Component's Disassembly (N_5)	VG	P	VP	F	VP	F	VP	VP	VP	P	P	F	P	F	VP	F	P	VP	VP	VP
Level of Integration (N_6)	VG	P	VP	F	VP	F	VP	VP	VP	P	P	F	P	F	VP	F	P	VP	VP	VP
Quantity of Parts (N_7)	VG	VP	P	G	VP	VG	G	P	F	F	P	VG	VP	G	F	VG	F	P	G	VP
Difficulty of Dismantling Part Attachment (N_8)	VG	P	VP	F	VP	F	VP	VP	VP	P	P	F	P	F	VP	F	P	VP	VP	VP
Amount of Different Materials (N_9)	G	G	G	F	G	F	G	P	G	P	P	F	G	F	G	F	P	G	G	G
Amount of Hazardous Materials (N_{10})	G	G	G	F	G	F	F	G	F	G	G	F	G	F	F	F	G	G	F	G
Component Weight (N_{11})	VG	F	P	P	F	G	G	F	VG	F	P	G	F	P	VG	G	F	P	G	F
Regulation Support (N_{12})	F	G	F	F	G	F	F	F	F	F	F	F	G	F	F	F	F	F	F	G
Customer Preference (N_{13})	F	G	F	F	G	F	F	F	F	F	F	F	G	F	F	F	F	F	F	G
Succedaneum Price (N_{14})	F	F	F	F	G	F	F	F	F	F	F	F	F	F	F	F	F	F	F	G